Exotics in Leptonic Machines

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Outline

- Introduction
- Selected topics on recent observations at leptonic machines
  - Enhancement/structure near 1.84 GeV
  - Charmonium-like particles (XYZ)
- Summary & Outlook

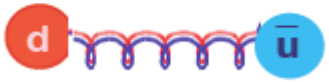
I apologize cannot cover all the topics in this interesting and charming field.

Introduction–Exotics

- **Exotic candidates because of self-coupling of gluons in QCD**
  - Bound gluons (glueball)
  - $q\bar{q}$–pair with an excited gluon (hybrids)
  - Multi-quark color singlet states
    - $q\bar{q}q\bar{q}$ (tetra-quark and molecular)
    - $q\bar{q}q\bar{q}q$ (penta-quark)
    - $q\bar{q}q\bar{q}q\bar{q}$ (six-quark and baryonium)

Glueball

Hybrid

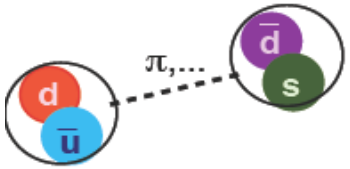


Pentaquark

H-dibaryon

Tetraquark

Molecule



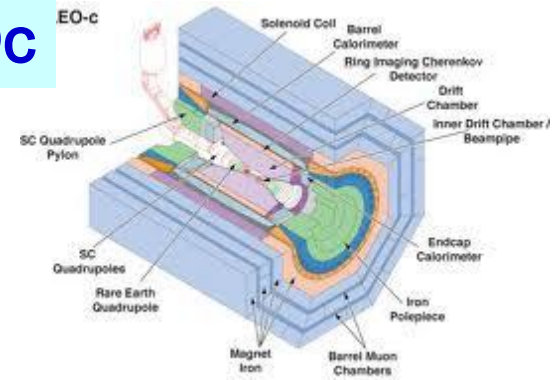
figures from arXiv:1403.1254, S. Olsen

Introduction–Leptonic machine

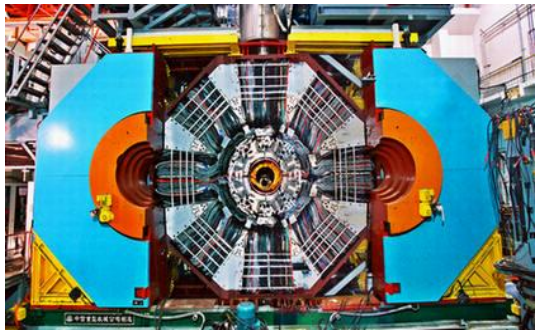
Charm factories
CLEOc and BESIII

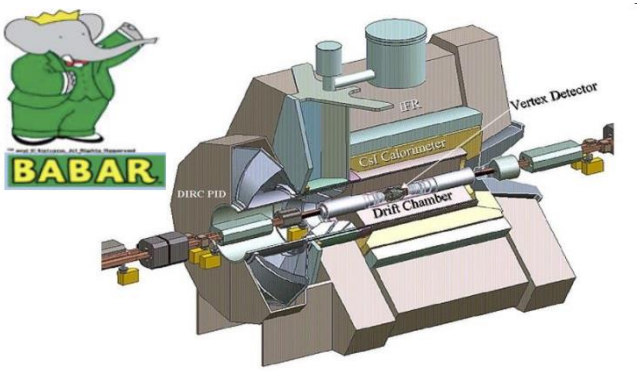
B factories
BaBar and Belle

CLEOc

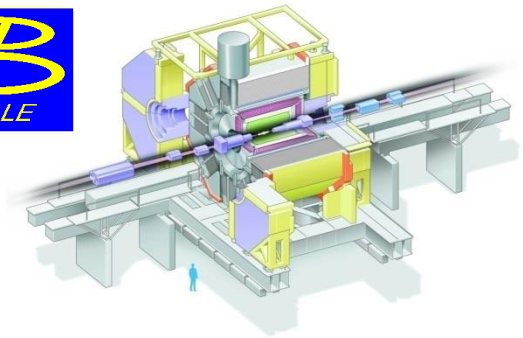


BESIII





BELLE



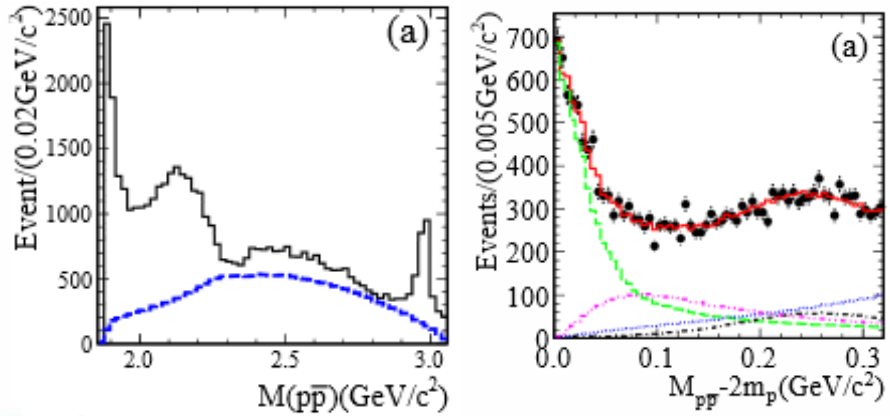
Structures near 1.84 GeV

- Recently observed or searched for structures near $p\bar{p}$ threshold
  - X($p\bar{p}$), X(1835), X(1840), X(1870), X(1810)
- I have to give up lots of interesting topics such as
  - Scalar particles: $a_0(980), f_0(980), f_0(1500), f_0(1710), f_0(2300)$, etc.
  - Tensors: $f_2'(1525), f_2(1810), f_2(2340)$
  - Enhancement near threshold of $p\Lambda$
  - More …

For $f_0(1500), f_0(1710), f_0(2300)$, *See T. Latham's talk.*

$p\,\bar{p}$ enhancement

Phys. Rev. Lett. 108 112003



$J/\psi \to \gamma p\bar{p}$

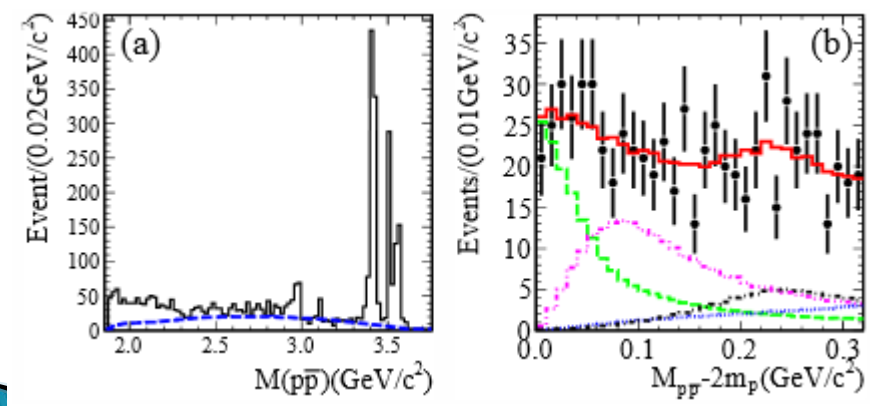
$M\ 1832^{+19}_{-5}\ (\text{stat.})^{+18}_{-17}\ (\text{syst.}) \pm 19\ (\text{model})\ \text{MeV}/c^2$

$\Gamma\ 13 \pm 39\ (\text{stat.})^{+10}_{-13}\ (\text{syst.}) \pm 4\ (\text{model})\ \text{MeV}/c^2$

$J^{PC} = 0^{-+}$

BESIII

PWA

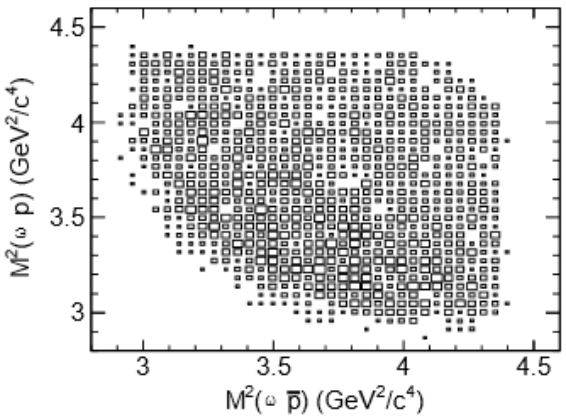


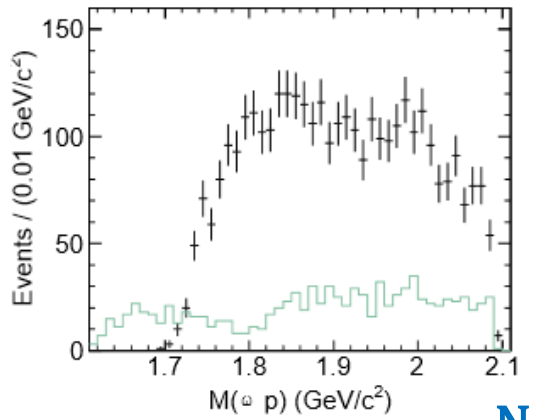
$\psi' \to \gamma p\bar{p}$

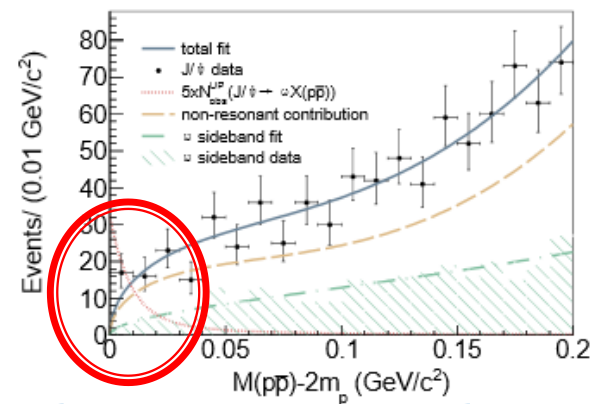
No obvious structure observed

$p\,\bar{p}$ enhancement cont.

- $J/\psi \to \omega p\bar{p}$ BESIII Phys. Rev. D 87 (2013) 112004







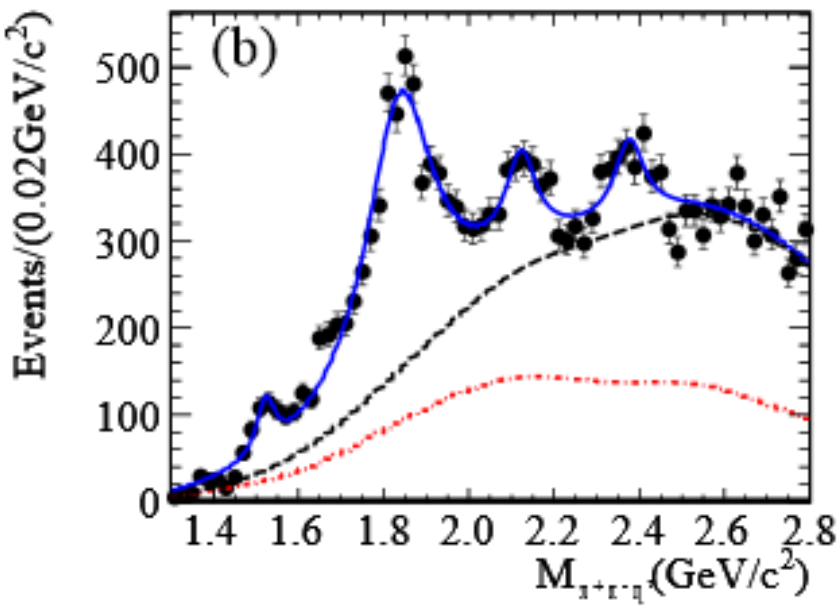
No obvious structure observed.

Disfavors the pure FSI interpretation for the $p\bar{p}$ threshold enhancement in the decay $J/\psi \to \gamma p\bar{p}$.

X(1835)

Phys. Rev. Lett. 106 (2011) 072002

- Via $J/\psi \to \gamma\pi^+\pi^-\eta'$



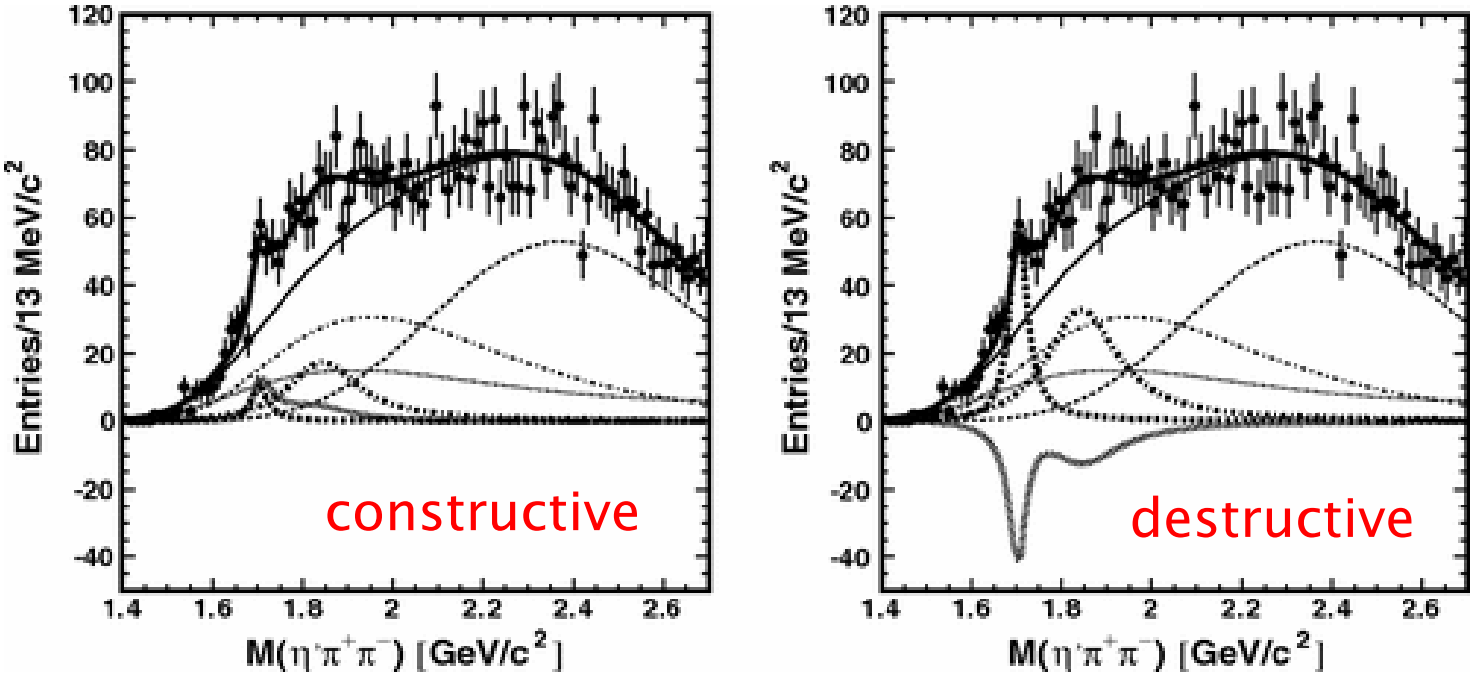
- $X(1835)$
  $M = 1836.5 \pm 3.0(\text{stat})^{+5.6}_{-2.1}(\text{syst})\ \text{MeV}/c^2$
  $\Gamma = 190 \pm 9(\text{stat})^{+38}_{-36}(\text{syst})\ \text{MeV}/c^2$
- $X(2120)$
  $M = 2122.4 \pm 6.7(\text{stat})^{+4.7}_{-2.7}(\text{syst})\ \text{MeV}/c^2$
  $\Gamma = 83 \pm 16(\text{stat})^{+31}_{-11}(\text{syst})\ \text{MeV}/c^2$
- $X(2370)$
  $M = 2376.3 \pm 8.7(\text{stat})^{+3.2}_{-4.3}(\text{syst})\ \text{MeV}/c^2$
  $\Gamma = 83 \pm 17(\text{stat})^{+44}_{-6}(\text{syst})\ \text{MeV}/c^2$

To determine spin and parity, **PWA** is needed.
X(1835) is consistent with a **pseudo-scalar**.

X(1835), cont

Phys. Rev. D 86, 052002

- Via $\gamma\gamma \to \pi^+\pi^-\eta'$



Interference between $X(1835)$ and $\eta(1760)$ is considered.

X(1835) cont.

Phys. Rev. D 89 (2014) 032003

Search X(1835) via $e^+e^- \to J/\psi + X(1835)$ at $\sqrt{s} \approx 10.6$GeV

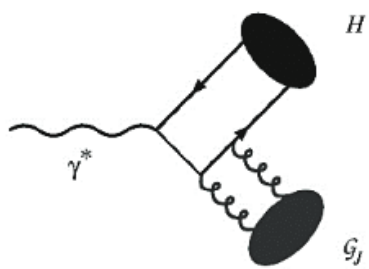
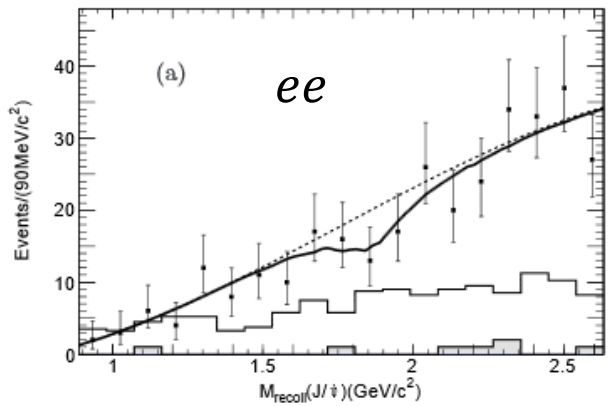
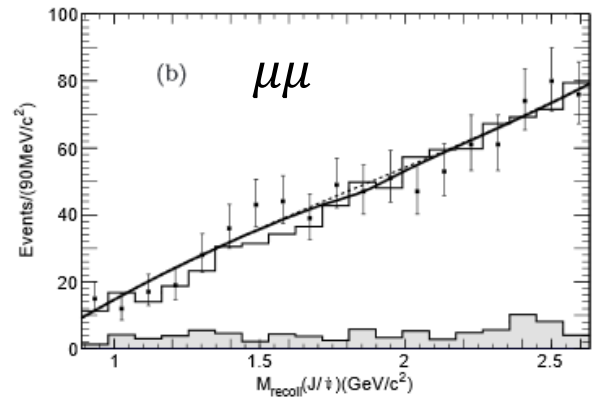


FIG. 1: Possible Feynman diagram for $\gamma^* \to H + \mathcal{G}_J$





No significant evidence is found to support the hypothesis of the X(1835) as a glueball produced in association with a J/ψ.

X(1810)

Phys. Rev. D 87 (2012) 032008

- Via $J/\psi \to \gamma\omega\phi$ BESIII PWA

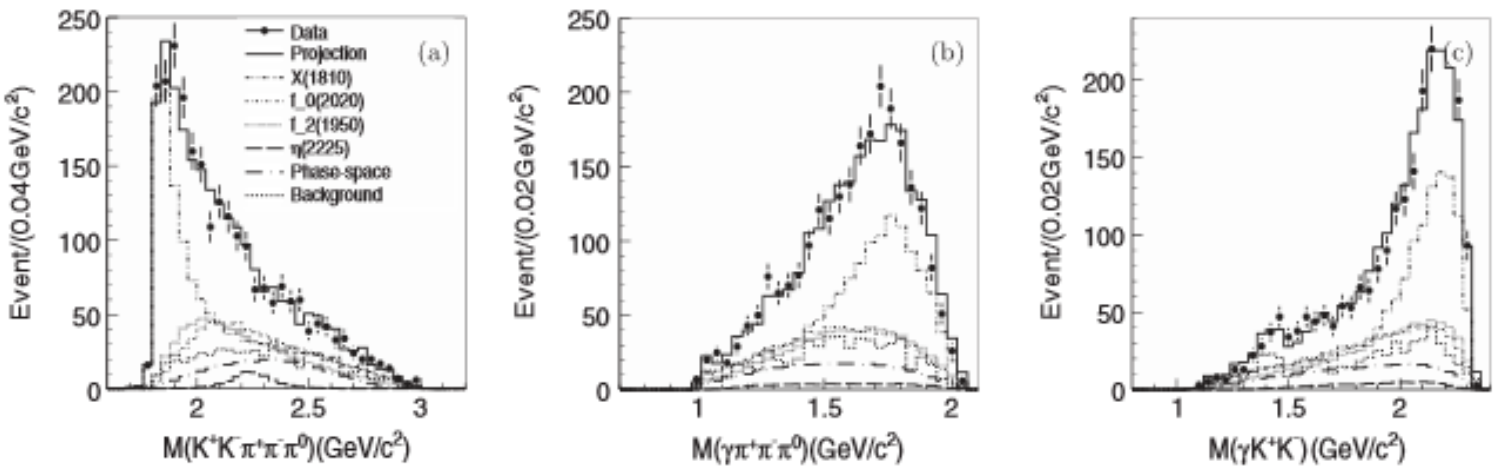


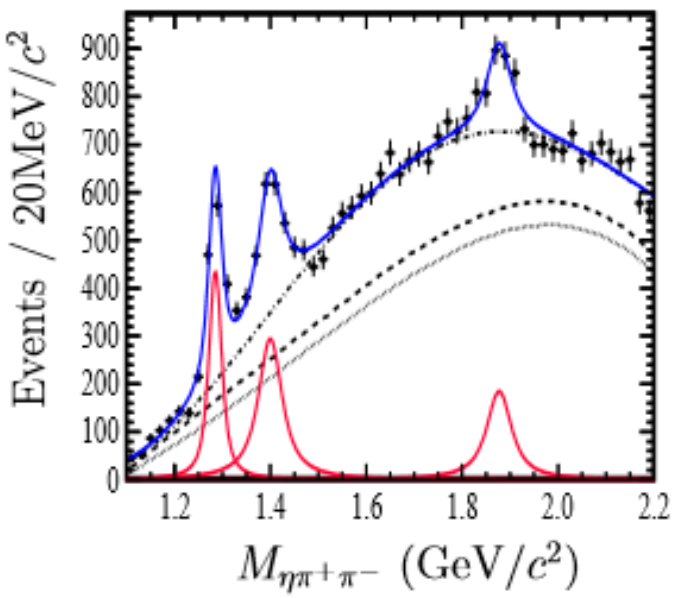
TABLE I. Results from the best PWA fit solution.

Resonance	J^{PC}	M(MeV/c^2)	Γ(MeV/c^2)	Events	$\Delta\mathcal{S}$	Δndf	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	1319 ± 52	783	4	$>30\sigma$
$f_2(1950)$	2^{++}	1944	472	665 ± 40	211	2	20.4σ
$f_0(2020)$	0^{++}	1992	442	715 ± 45	100	2	13.9σ
$\eta(2225)$	0^{-+}	2226	185	70 ± 30	23	2	6.4σ
Coherent nonresonant component	0^{-+}	...	...	319 ± 24	45	2	9.1σ

X(1870)

BESIII Phys. Rev. Lett. 107 (2011) 182001

- Via $J/\psi \to \omega\eta\pi^+\pi^-$, where $J/\psi \to \omega X(1870)$, $X(1870) \to a^{\pm}(980)\pi^{\mp}$



First measurement

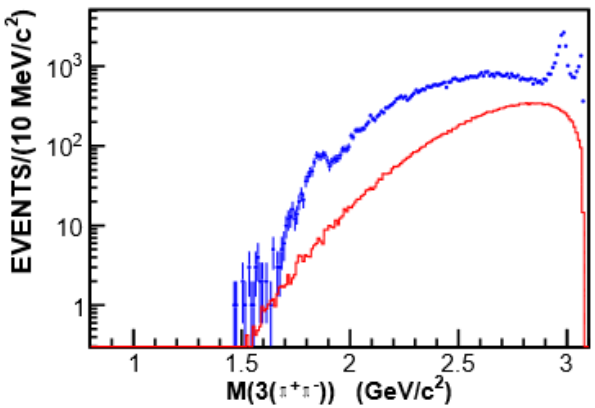
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}$ (10^{-4})
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

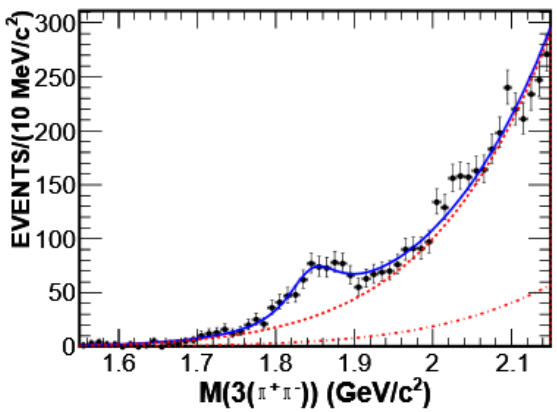
PWA is needed to determine the spin and parity of X(1870).

X(1840)

Phys. Rev. D 88 (2013) 091502

- $J/\psi \to \gamma 3(\pi^+\pi^-)$ BESIII





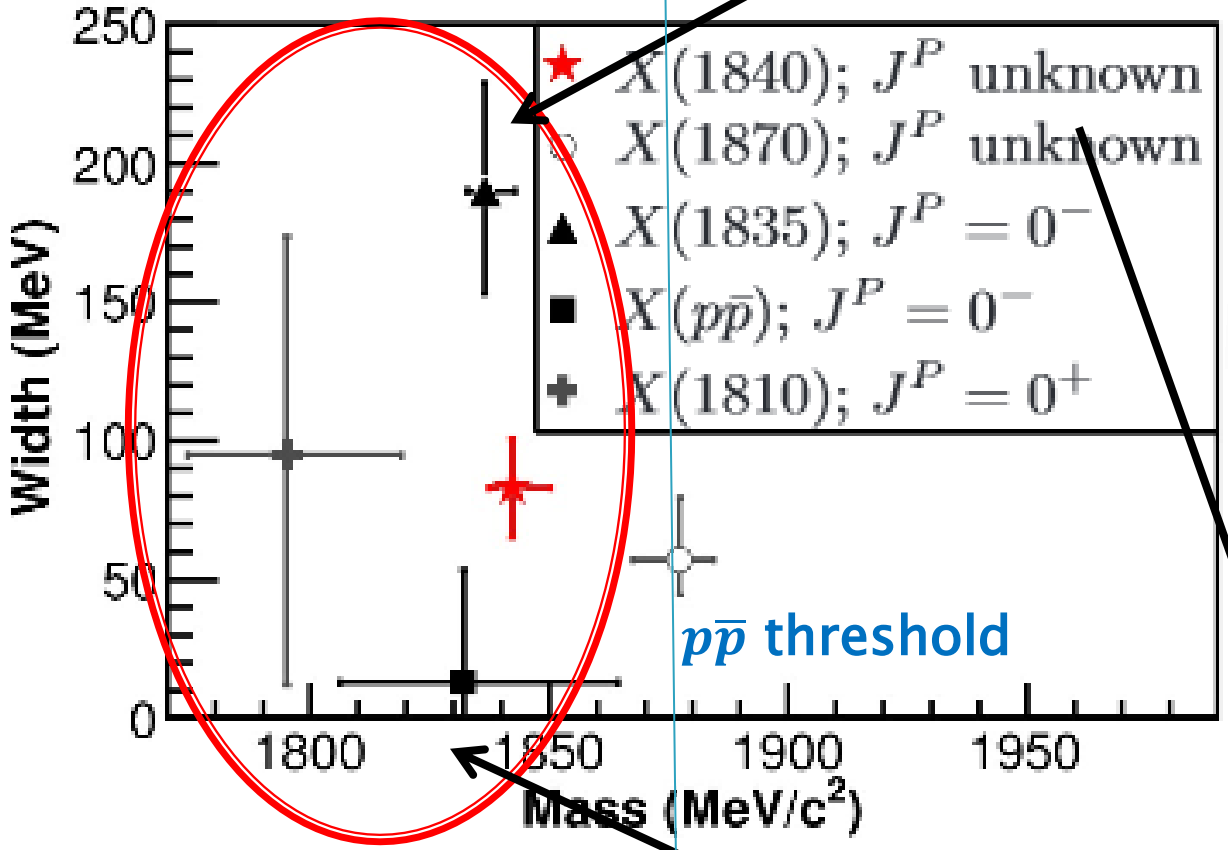
- Statistical significance: 7.6σ
- $M = 1842.2 \pm 4.2^{+7.1}_{-2.6}$ MeV/c^2
- $\Gamma = 83 \pm 14 \pm 11$ MeV

PWA is needed to determine the spin and parity of X(1840).

No η' signal is found.

A partial summary

Not like a glueball



$p\bar{p}$ threshold

Same source or not ?

Bayonia?
Glueball?
Hybrid?
Threshold effect?
Other possibilities?

PWA is needed.

J/ψ radiative decay

Not found in ψ' radiative decay
Not like a pure FSI

Charmonium-like exotics

- New information on $X(3872)$
- New information on Y states
  - Babar and Belle update $e^+e^- \to \gamma_{ISR}\, \pi^+\pi^- J/\psi$, $e^+e^- \to \gamma_{ISR}\, \pi^+\pi^- \psi(2S)$ with larger luminosities
  - BESIII: $\pi^+\pi^- h_c$
- Charged Z
  - $Z_c(3900)$ and its partners
  - Z_{cs} search via $K^+K^- J/\psi$
  - $Z_b(10610)$and $Z_b(10650)$

For $Z_c(4430)$, see Ye Chen's talk

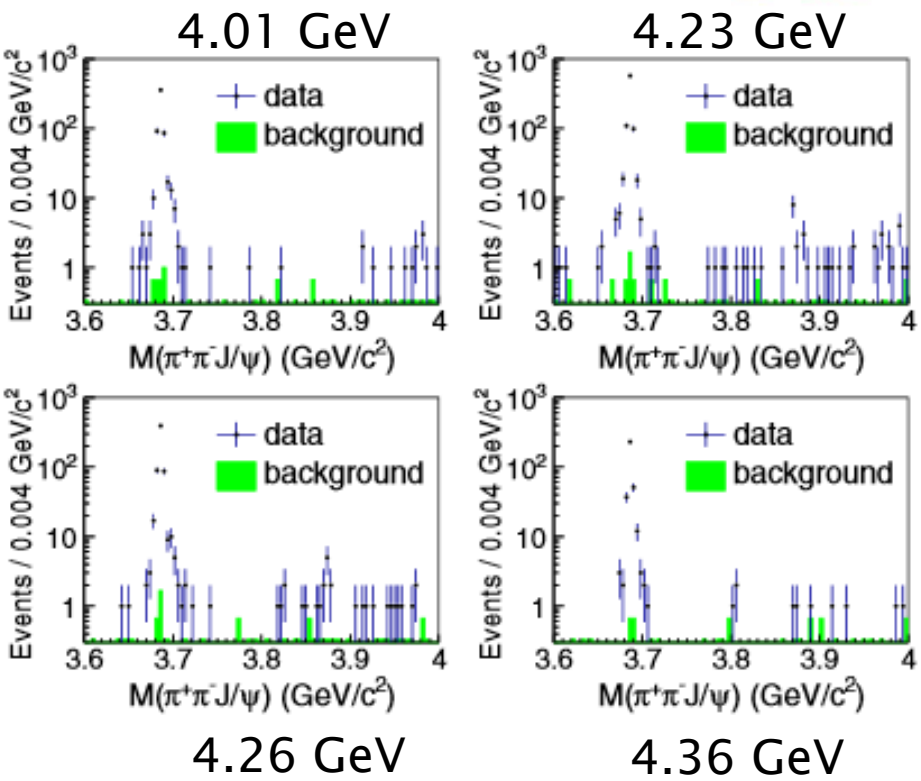
Overview of $X(3872)$

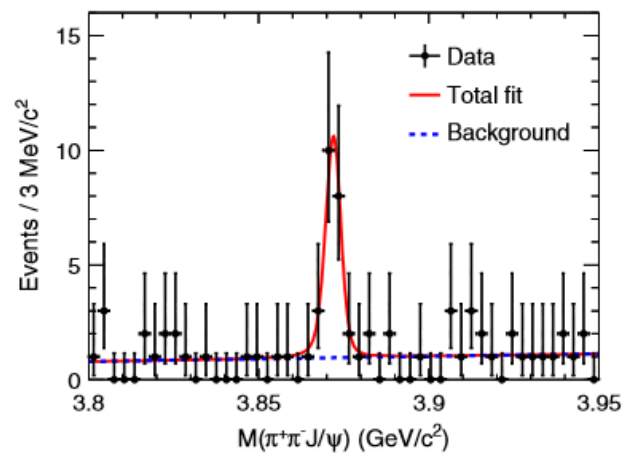
- First observed in $B \to K(\pi^+\pi^- J/\psi)$ 2003
  - mass: close to $D^{*0}D^0$ threshold
  - width: very narrow
- $J^{PC}=1^{++}$ [CDF and LHCb]
- Decay BR:
  - open charm ~ 50%, charmonium~O(%)
- Nature (many possibilities)
  - Charmonium state: $\chi_{c1}(2P)$
  - D^0D^{*0} module
  - Hybrid: mass too low
  - Tetra-quark: no charged partner be found
- Production
  - in pp collision and B decays
  - $e^+e^- \to \gamma X(3872)$ [NEW, see next slide]

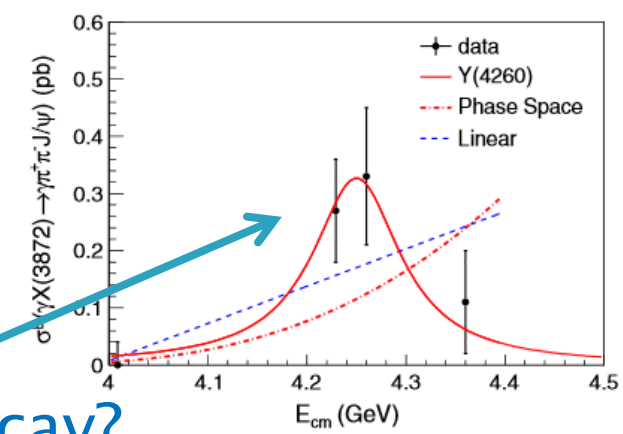
X(3872), new production mode

Phys. Rev. Lett. 112, 092001

- $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ BESIII



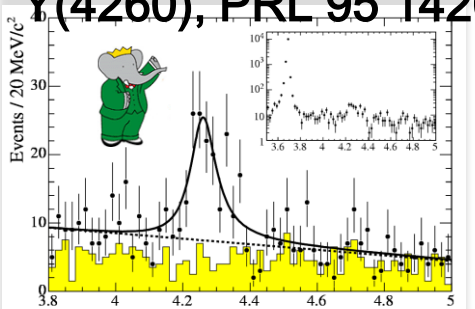


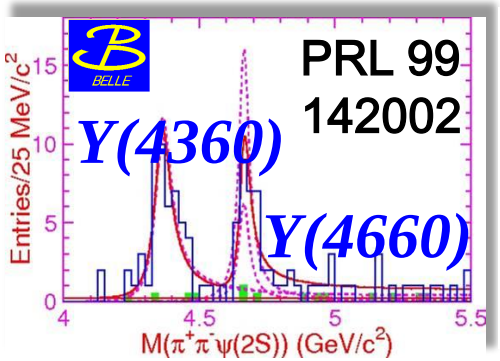


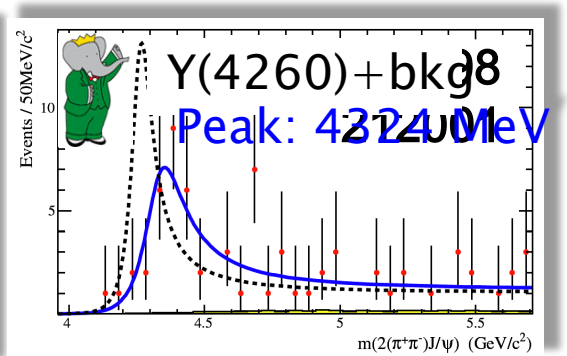
From $Y(4260)$ decay?

Y states: 1^{--} states from ISR

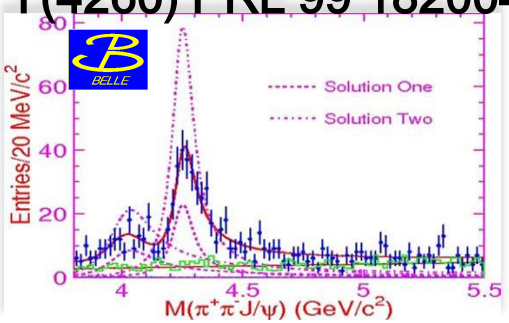
Y(4260), PRL 95 142001

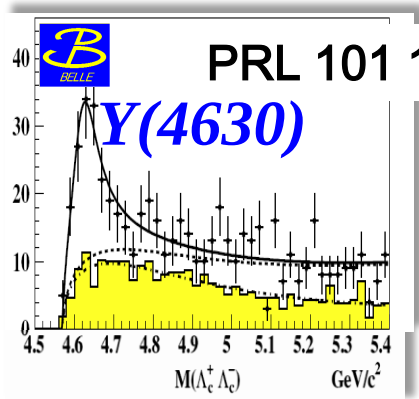


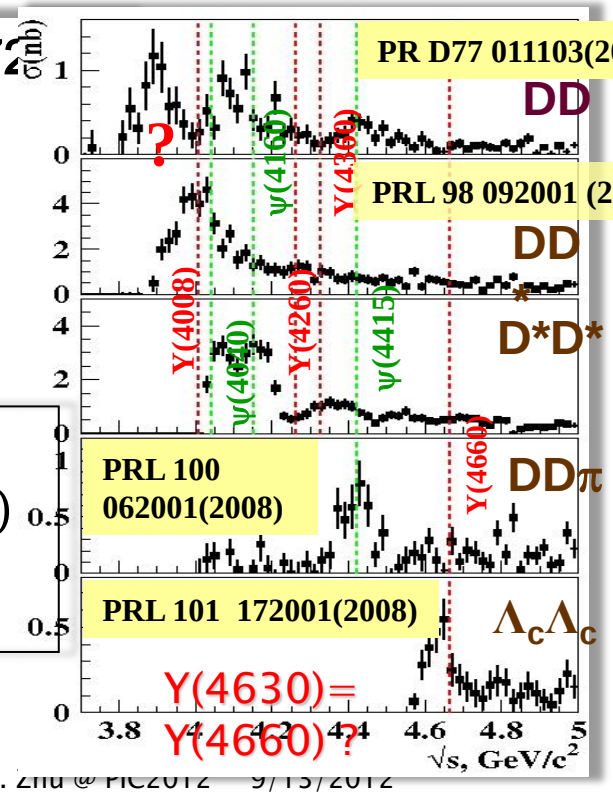




Y(4260) PRL 99 182004







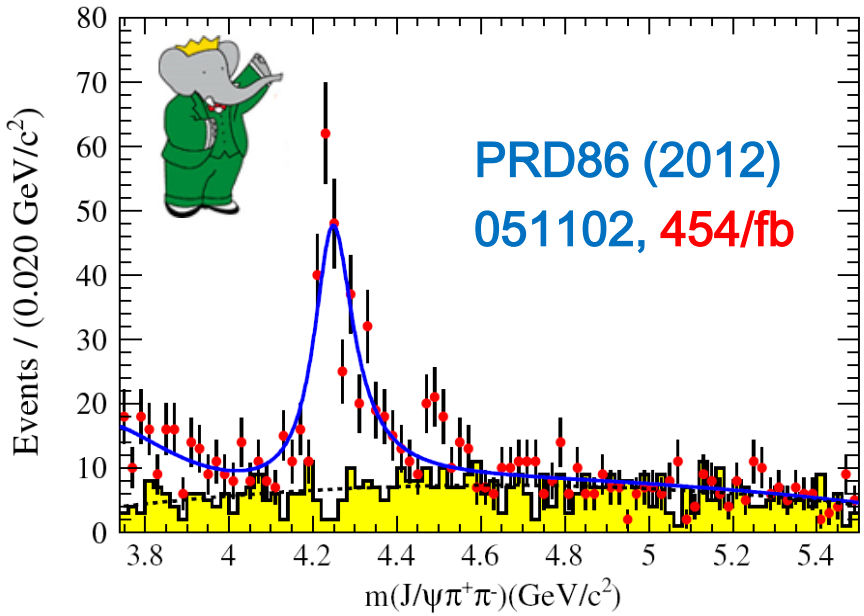
Too many Y states!

Y(4008)
Y(4260)
Y(4360)
Y(4660)
Y(4630)

Large partial width to $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$

No sign of Y→D(*)D(*)

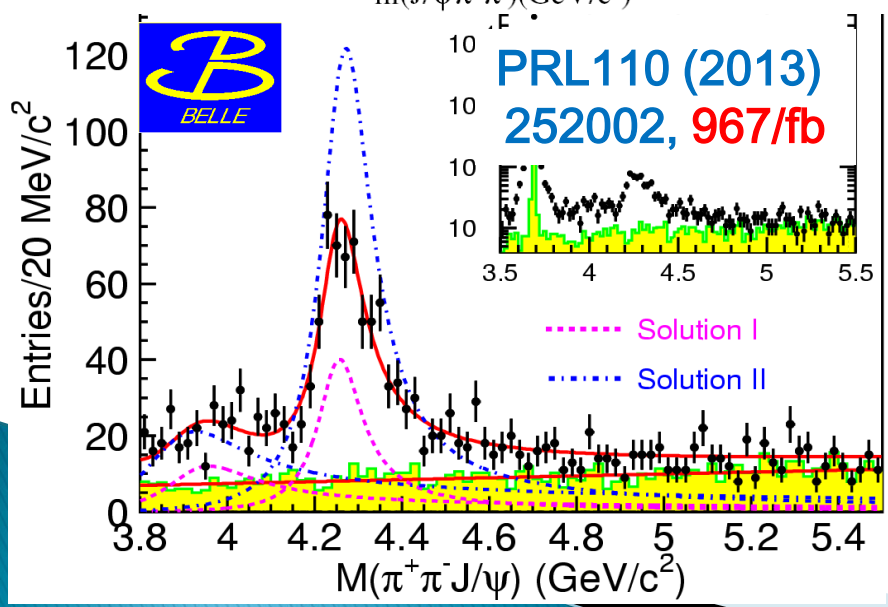
Y states: update by Belle and Babar



$$e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$$

Significant Y(4260) is found.

Not confirm Y(4008).
Fit method?

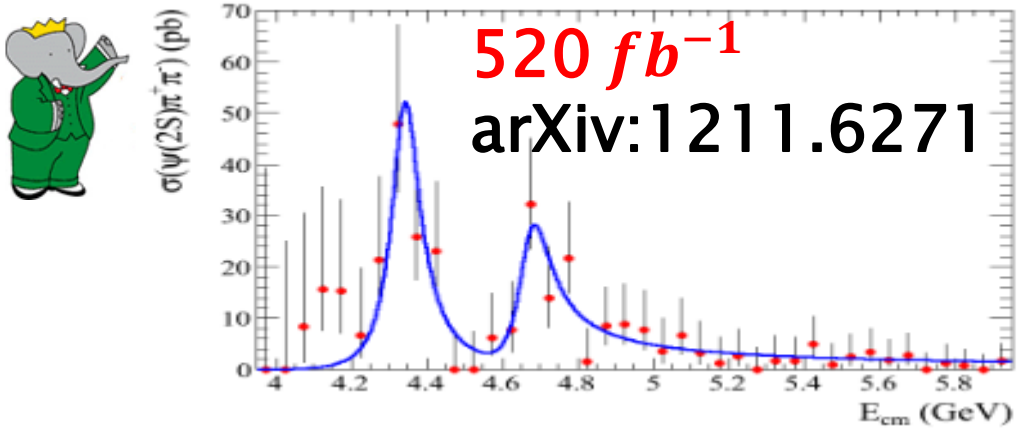


Still observe two resonances Y(4008) and Y(4260).

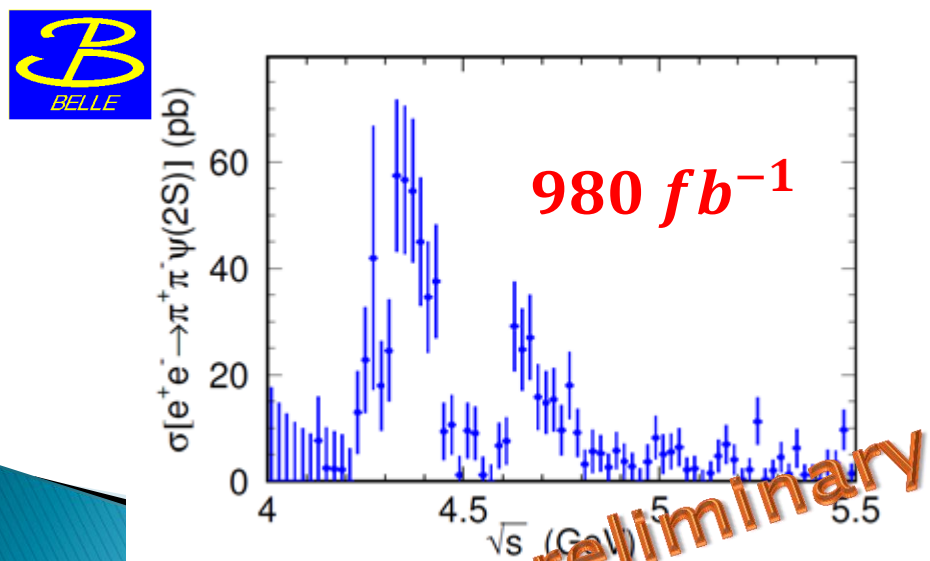
Agrees with Belle's previous results.

Y states: update cont.

$e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(2S)$



Fitted with $Y(4360)$, $Y(4660)$, two solutions.



Fitted with $Y(4260)$, $Y(4360)$, $Y(4660)$.

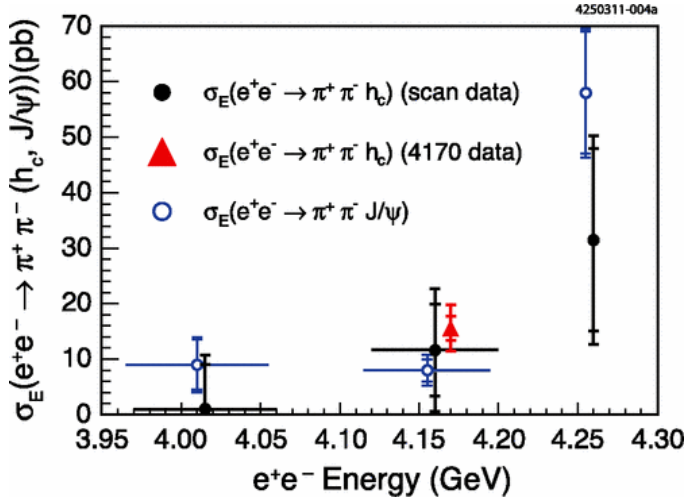
The significance of $Y(4260)$ is only 2.1σ, but its effect on others is large.

From C.P. Shen

Structures from $\pi^+\pi^- h_c$

CLEOc

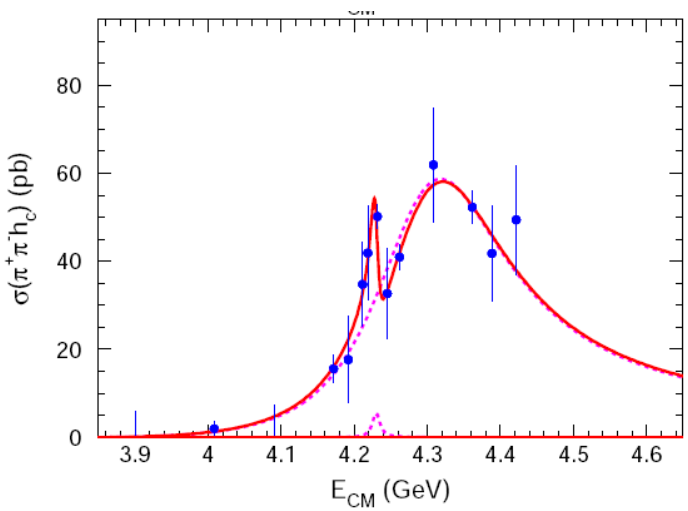
Phys. Rev. Lett. 107, 041803



BESIII

Phys. Rev. Lett. 111, 242001

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	$n_{h_c}^{obs}$	$\sigma(e^+e^- \to \pi^+\pi^- h_c)$ (pb)
3.900	52.8	<2.3	<8.3
4.009	482.0	<13	<5.0
4.090	51.0	<6.0	<13
.190	43.0	8.8 ± 4.9	17.7 ± 9.8 ± 1.6 ± 2.8
.210	54.7	21.7 ± 5.9	34.8 ± 9.5 ± 3.2 ± 5.5
.220	54.6	26.6 ± 6.8	41.9 ± 10.7 ± 3.8 ± 6.6
4.230	1090.0	646 ± 33	50.2 ± 2.7 ± 4.6 ± 7.9
4.245	56.0	22.6 ± 7.1	32.7 ± 10.3 ± 3.0 ± 5.1
4.260	826.8	416 ± 28	41.0 ± 2.8 ± 3.7 ± 6.4
4.310	44.9	34.6 ± 7.2	61.9 ± 12.9 ± 5.6 ± 9.7
4.360	544.5	357 ± 25	52.3 ± 3.7 ± 4.8 ± 8.2
4.390	55.1	30.0 ± 7.8	41.8 ± 10.8 ± 3.8 ± 6.6
4.420	44.7	29.1 ± 7.3	49.4 ± 12.4 ± 4.5 ± 7.6

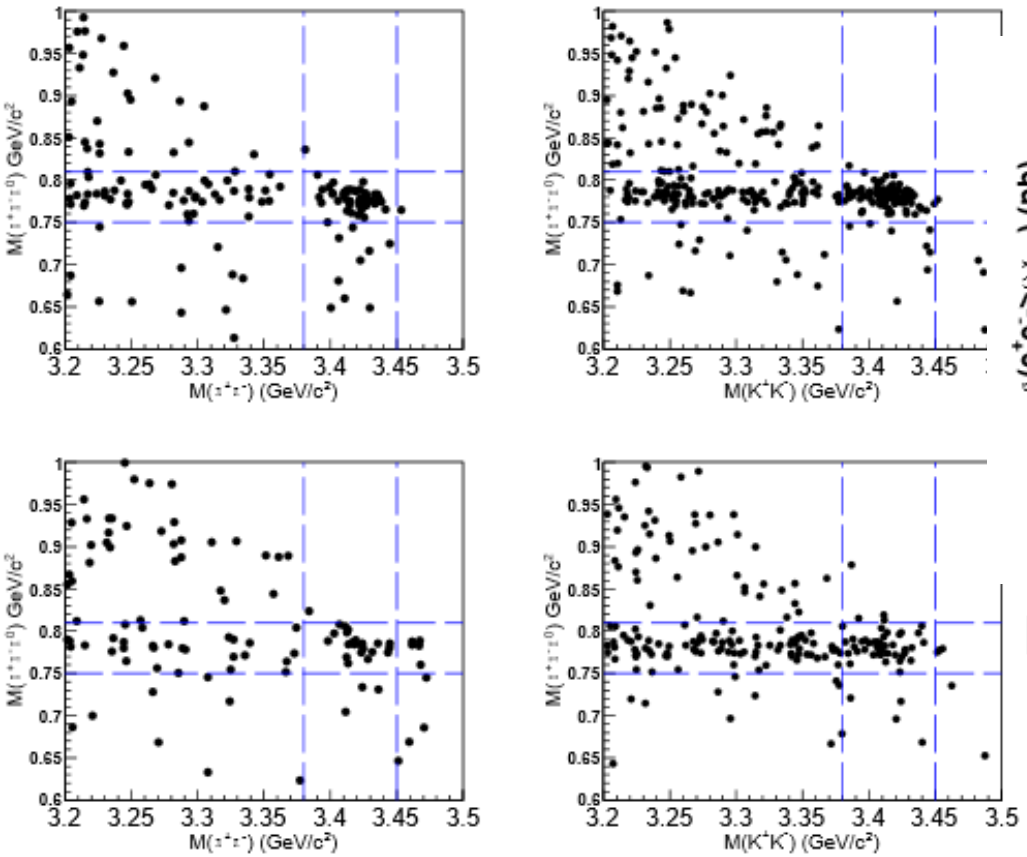


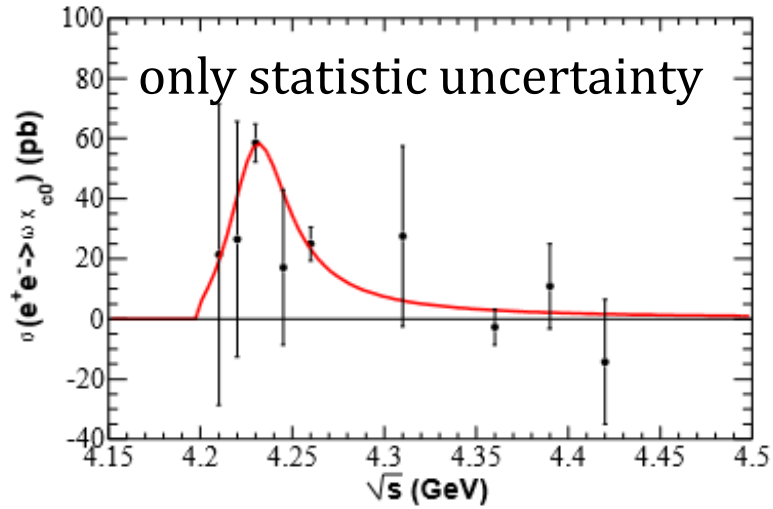
An individual work based on the combined BESIII and CLEOc data.

Fit with a narrow Y(4220) and a wide Y(4290).

C. Z. Yuan arXiv:1310.0280

$e^+e^- \to \omega\chi_{c0}$ BESIII preliminary



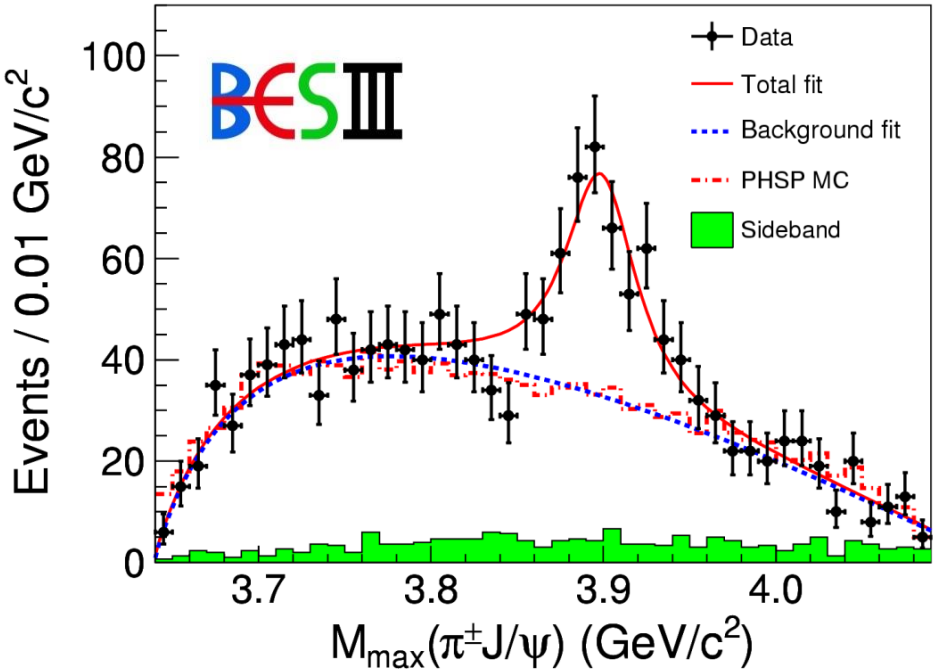


Fit with a single BW assumption, mass lower than 4.26 GeV.

No signal of $\omega\chi_{c1}$ or $\omega\chi\_c2$ found.
Disfavor $Y(4260)$ is a $\omega\chi_{c1}$ molecule.

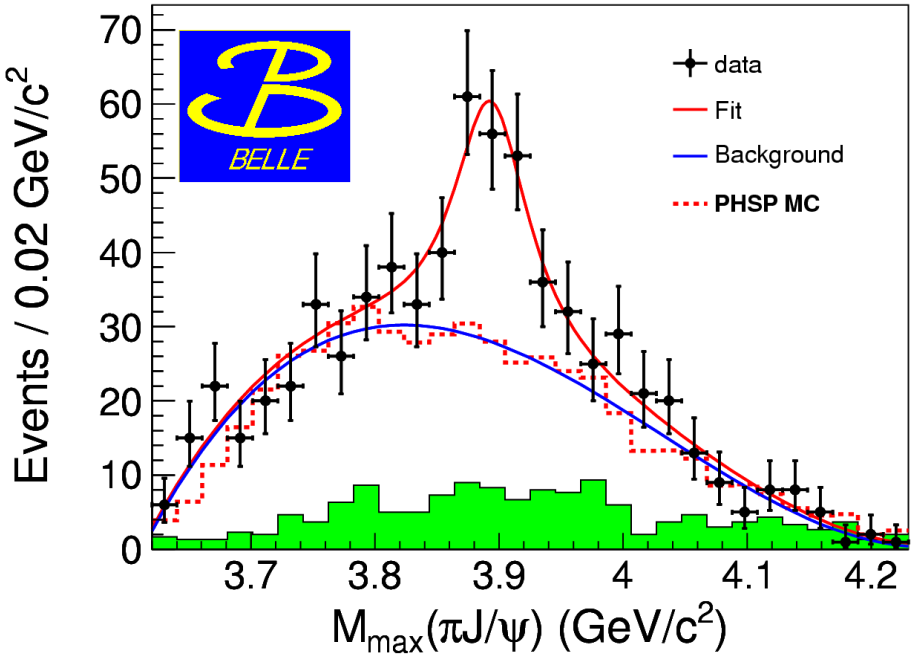
$Z_c(3900)$: observed in BESIII and Belle

At 4.26 GeV: PRL. 110, 252001



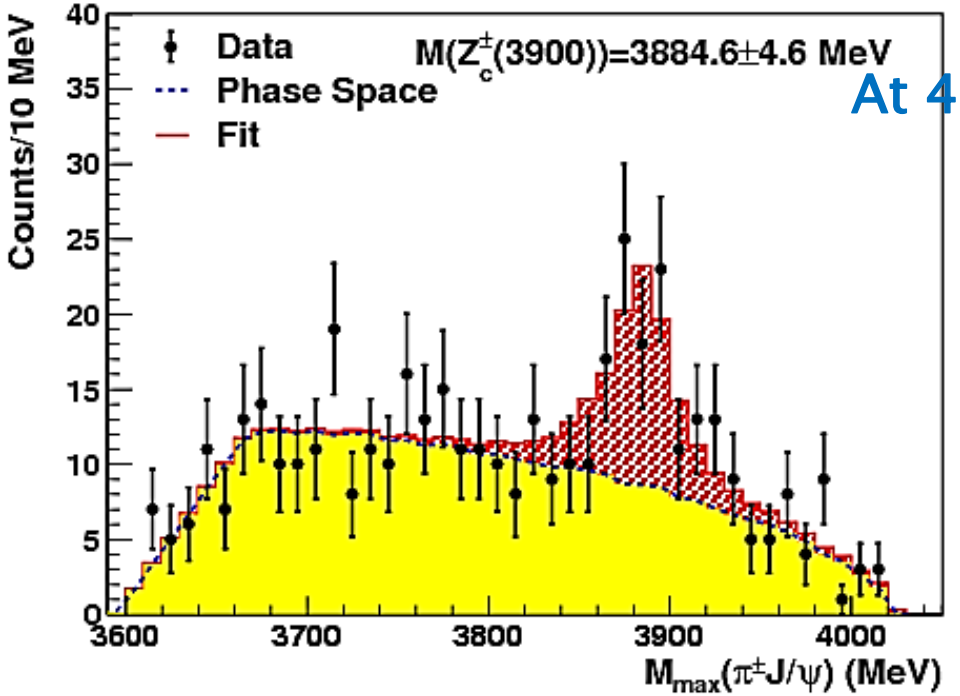
- M = 3899.0±3.6±4.9 MeV
- Γ = 46±10±20 MeV
- 307 ± 48 events
- >8σ

ISR: PRL 110, 252002



- M = 3894.5±6.6±4.5 MeV
- Γ = 63±24±26 MeV
- 159 ± 49 events
- >5.2σ

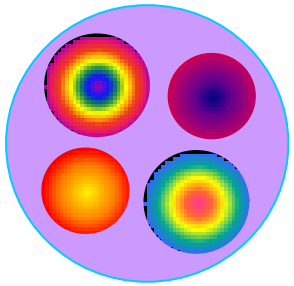
$Z_c(3900)$: confirmed by an analysis of CLEOc data



At 4.17 GeV: PLB 727 366–370

- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ

- Couples to $c\bar{c}$
- Has electric charge
- At least 4-quarks



- DD* molecule?
- Tetraquark?
- Cusp?
- Threshold effect?
- …

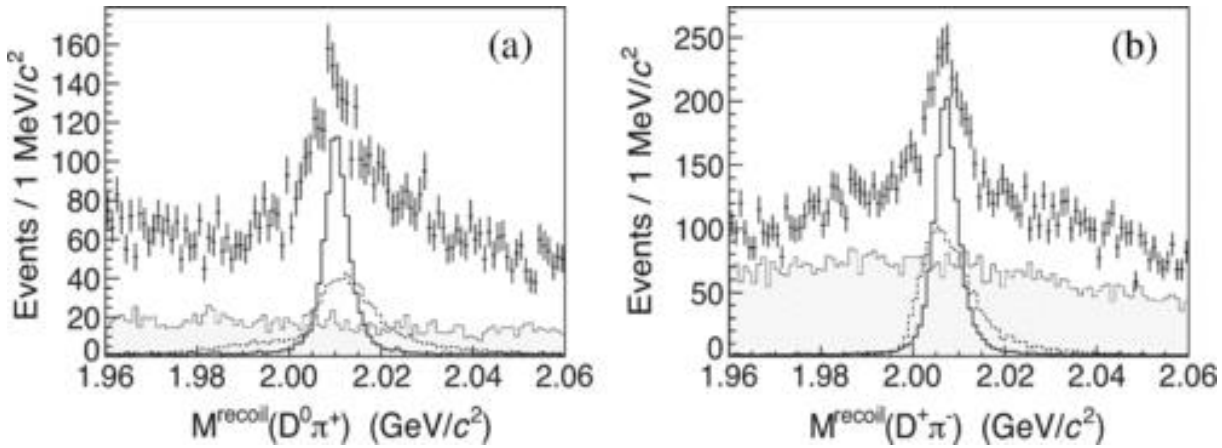
$Z_c(3885)$

Phys. Rev. Lett. 112, 022001

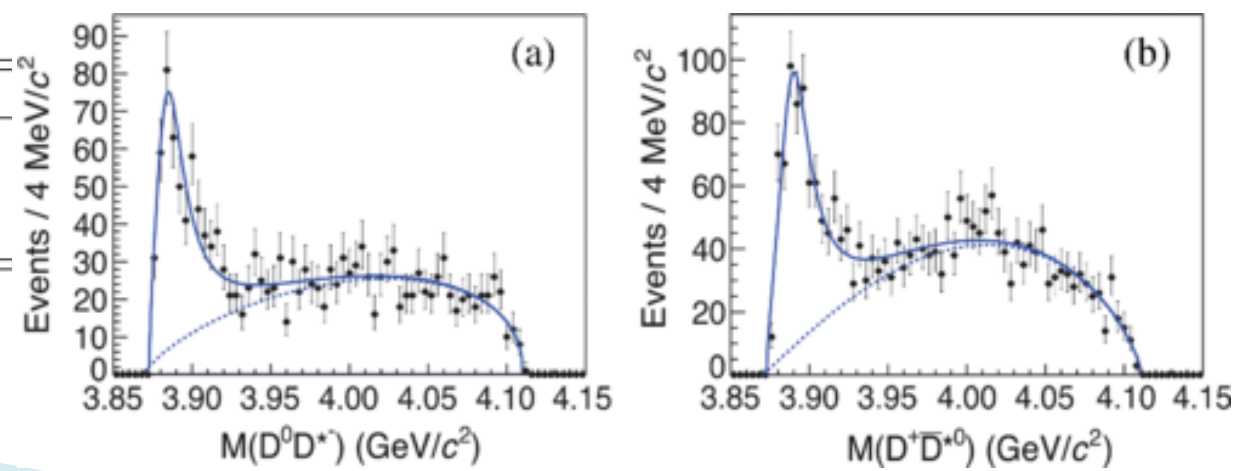
- $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ at 4.26 GeV

BESIII

$\sqrt{s}$=4.26 GeV
$525pb^{-1}$
Favor $J^P = 1^+$



	$Z_c(3885) \to D\bar{D}^*$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$



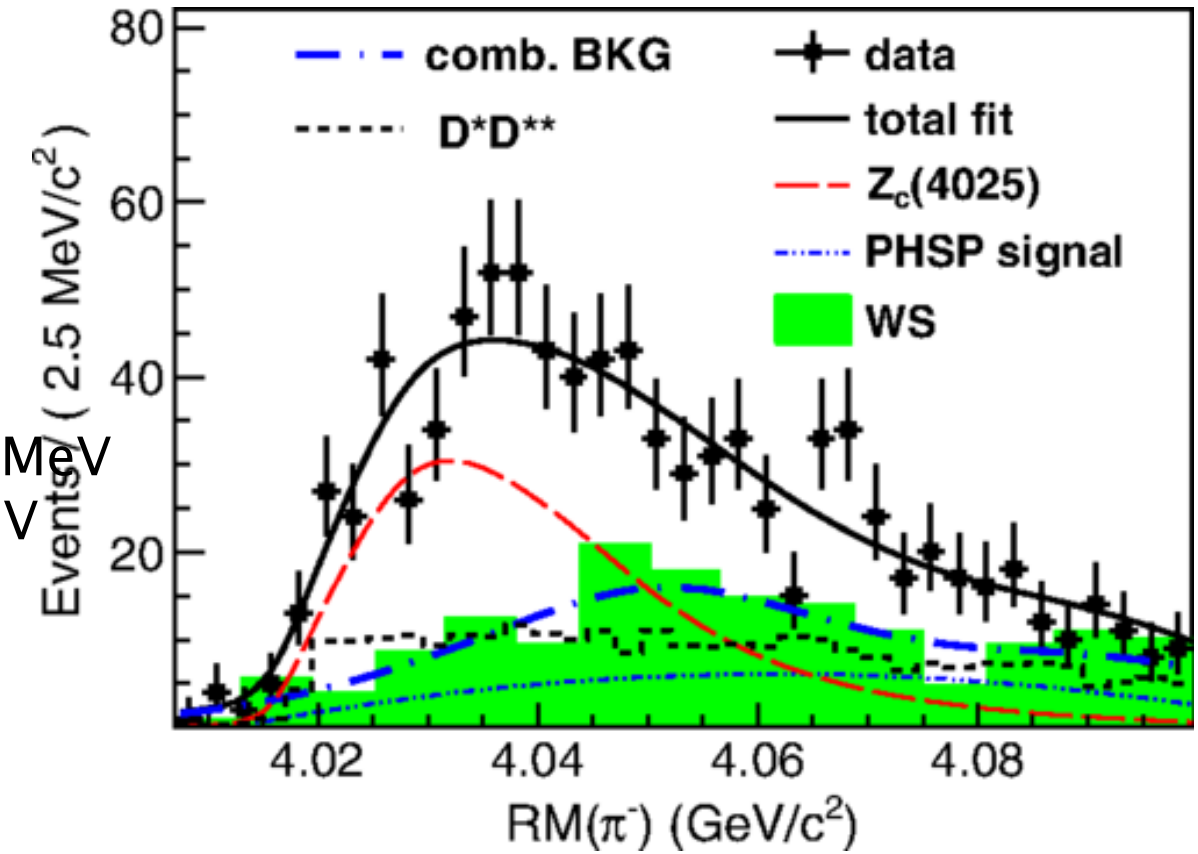
$Z_c(4025)$

Phys. Rev. Lett. 112, 132001

- $e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$ at 4.26 GeV

BESIII

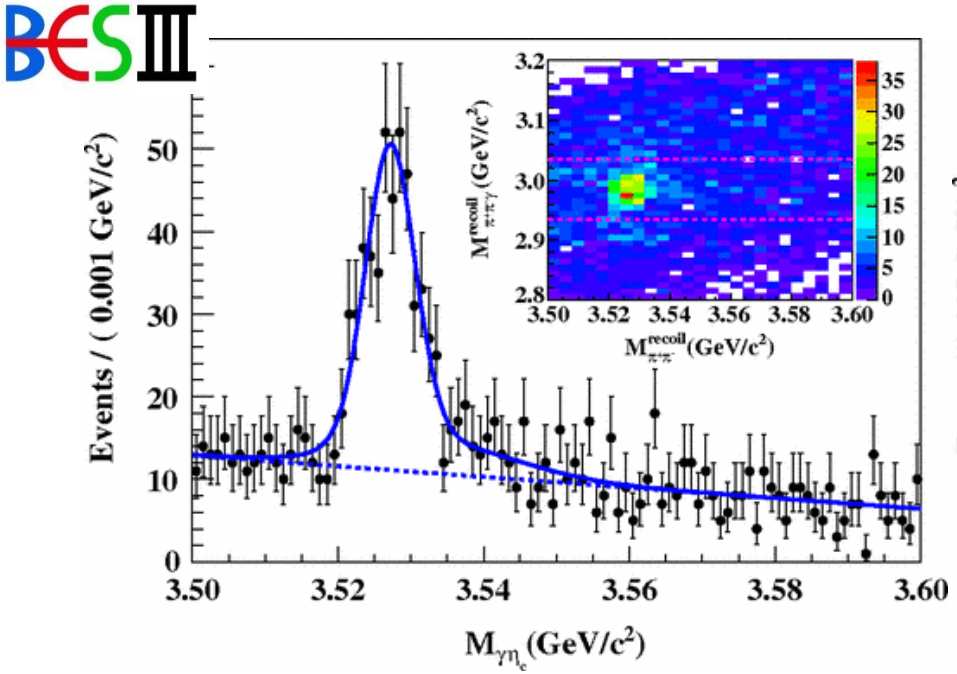
$\sqrt{s} = 4.26$ GeV
$827\ pb^{-1}$
$M =$ (4026.3±2.6±3.7)MeV
$\Gamma =$ (24.8±5.6±7.7)MeV

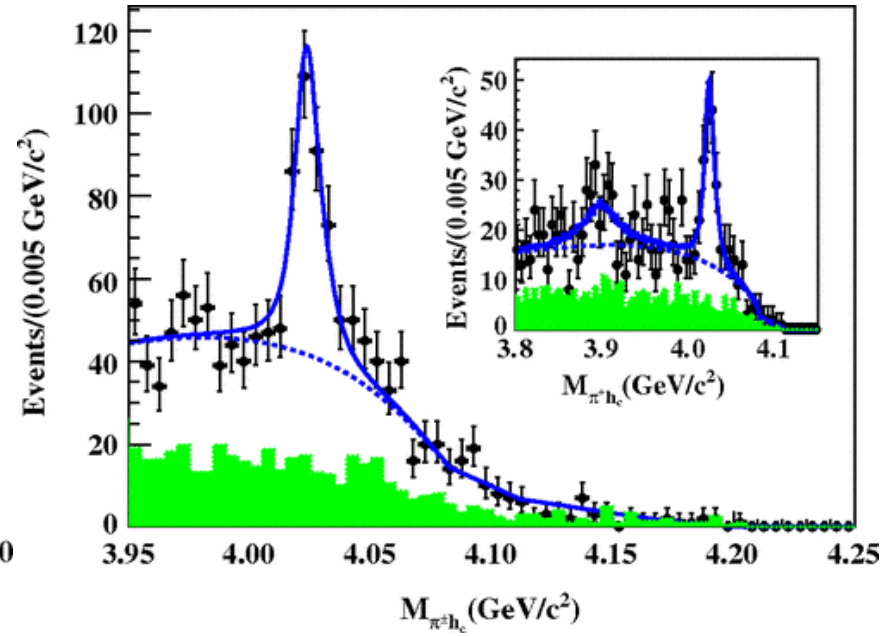


$Z_c(4020)$: charged

Phys. Rev. Lett. 111, 242001

- $e^+e^- \to \pi^+\pi^- h_c$ from 3.90 to 4.42 GeV (13 ·)





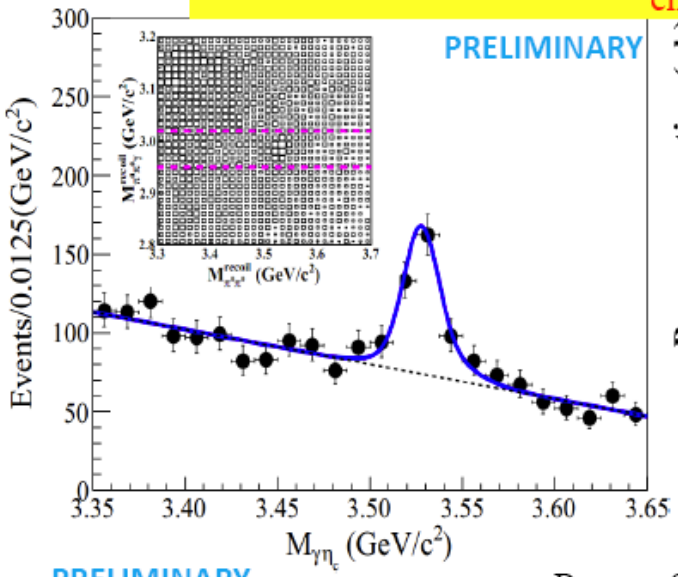
$$M = (4022.9 \pm 0.8 \pm 2.7)\ MeV/c^2$$
$$\Gamma = (7.9 \pm 2.7 \pm 2.6)\ MeV$$

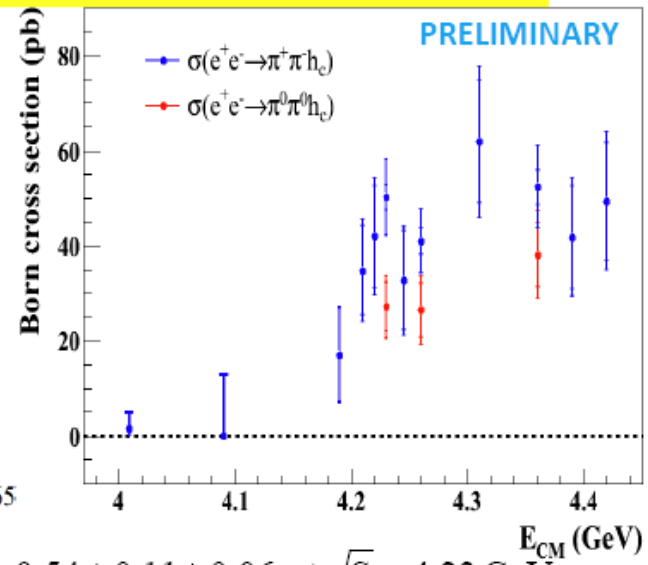
$Z_c(4020)$: neutral

BESIII

Observation of $e^+e^- \to \pi^0\pi^0 h_c(1P)$

Summed results at E_{cm}=4.23, 4.26, 4.36GeV





PRELIMINARY

For $R_{\pi\pi h_c} = \dfrac{\sigma(\text{neutral})}{\sigma(\text{charged})}$,

$R_{\pi\pi h_c} = 0.54 \pm 0.11 \pm 0.06$ at $\sqrt{S} = 4.23$ GeV,

$R_{\pi\pi h_c} = 0.64 \pm 0.14 \pm 0.10$ at $\sqrt{S} = 4.26$ GeV,

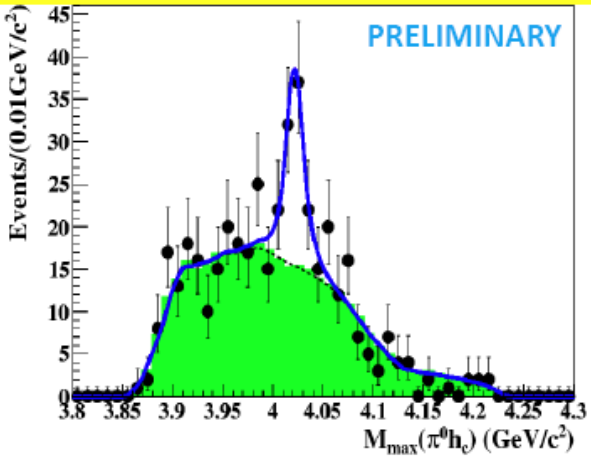
$R_{\pi\pi h_c} = 0.73 \pm 0.14 \pm 0.10$ at $\sqrt{S} = 4.36$ GeV,

$Z_c(4020)$: neutral cont.

BESIII

$$e^+e^- \to \pi^0 Z_c^0(4020) \to \pi^0\pi^0 h_c(1P)$$

Summed results at E_{cm}=4.23, 4.26, 4.36GeV



Simultaneous fit to 4.23/4.26/4.36GeV Data and 16 η_c modes;

$\Gamma(Z_c^0(4020))$ is fixed to value of $\Gamma(Z_c^{\pm}(4020))$;

Interference is neglected;

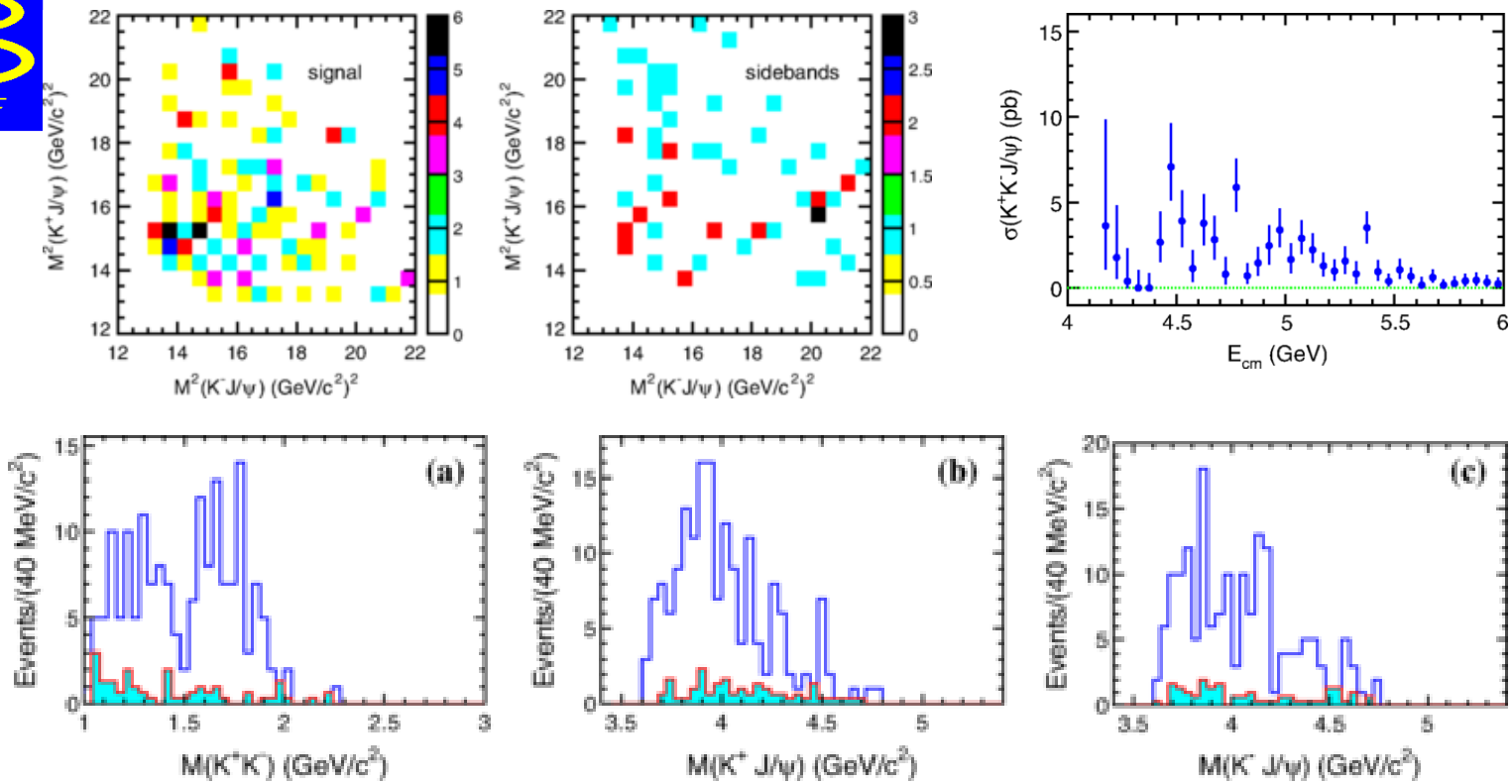
$M(Z_c^0(4020)) = 4023.6 \pm 2.2 \pm 3.9\ \mathrm{MeV/c^2}$;

Significance : $> 5\sigma$.

Z_{cs} search

Phys. Rev. D 89, 72015

- Belle update K^+K^-J/ψ to Dalitz Plot

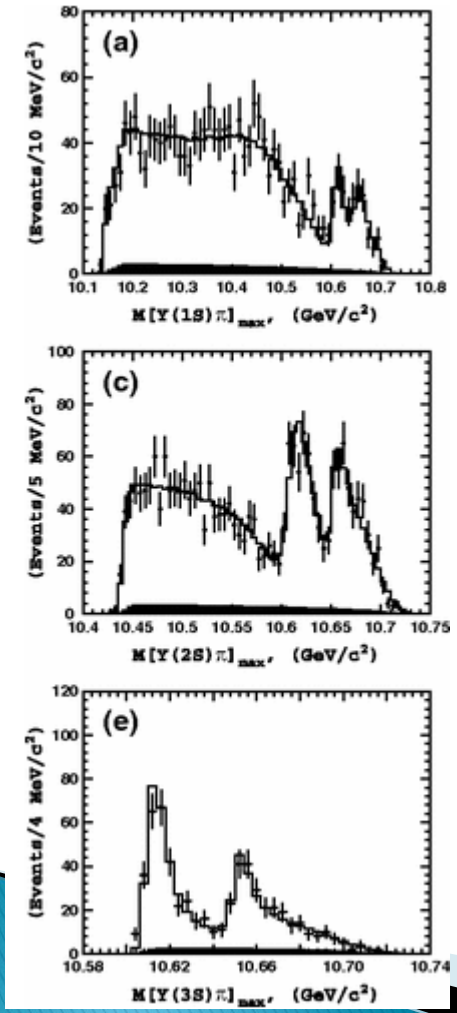


No evident structure in $K^{\pm}J/\psi$ mass distribution under current statistics

$Z_b(10610), Z_b(10650)$: charged

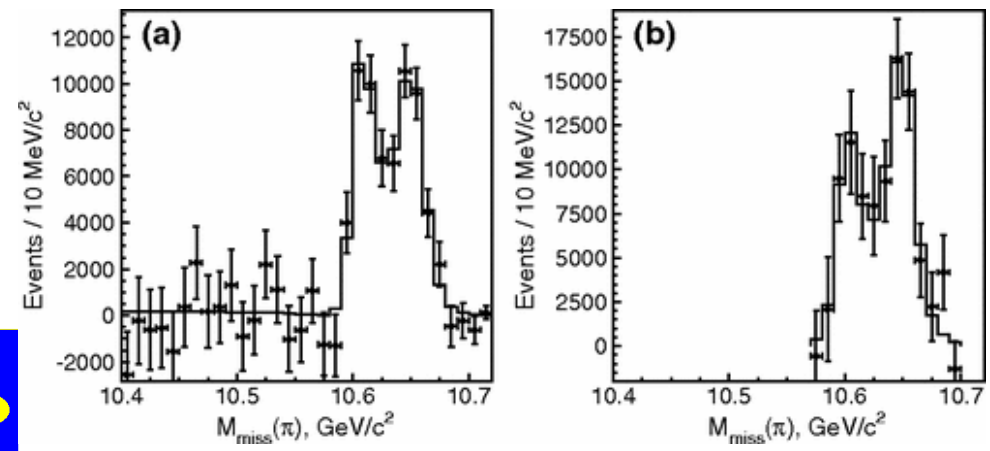
$e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

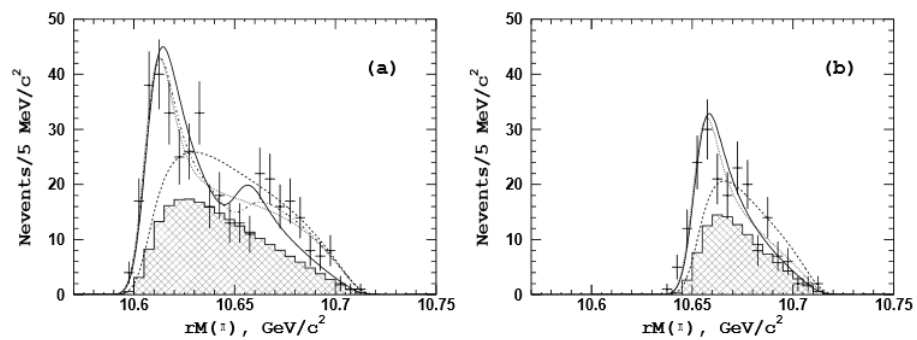
Phys. Rev. D 89, 72015



$e^+e^- \to \pi^+\pi^- h_b(\mathrm{mP})$

Phys. Rev. D 89, 72015





$\Upsilon(10860) \to Z_b(10610)^{\pm}\pi^{\mp} \to [B\bar{B}^*]^{\pm}\pi^{\mp}$

$\Upsilon(10860) \to Z_b(10650)^{\pm}\pi^{\mp} \to [B^*\bar{B}^*]^{\pm}\pi^{\mp}$

arXiv: 1209.6450

Partial summary of Z

- If we assume
  - $Z_c(3900)$ and $Z_c(3885)$ are a same state Z_c
  - $Z_c(4020)$ and $Z_c(4025)$ are a same state $Z_c{}'$

Only coincidence?

$Z_b(10610)$
$\pi\Upsilon(nS)$
$B\bar{B}^*$
$\pi h_b(mP)$

$Z_b(10650)$
$\pi\Upsilon(nS)$
$B\bar{B}^*, B^*\bar{B}^*$
$\pi h_b(mP)$

More excited states?
Other prod. modes?

$Z_c(4430)$
or
$Z_c(4470)$

Z_c
$\pi\, J/\psi$
$D\,\bar{D}^*$

$Z_c{}'$
$D^*\bar{D}^*$
πh_c

$Z_c{}'$ neutral
$\pi^0\, h_c$

Summary

- Leptonic machines produce exotics. These particles are unexpected, weird and strange, while also tantalizing, charming and interesting.
- Some structures are observed near $p\bar{p}$ threshold with similar masses.
  - Are they from same source? Are they baryonia, glueball or hybrid? For some cases, PWA is needed to determine the spin and parity. Search via more modes will help to reveal the veil.
- Lots of progress in XYZ studies in e^+e^- experiments
  - Observation of $e^+e^- \to \gamma X(3872)$
  - New information on the Y's from BaBar, Belle and BESIII.
  - Confirmed exotic state seems at least four quarks, $\boldsymbol{Z_c(3900)}$
  - Observation of more Z_c' at BESIII
- Exciting future!

Thanks a lot!